SN 1996cr: Confirmation of a Luminous Type IIn Supernova in the Circinus Galaxy

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Abstract. We have recently confirmed SN 1996cr as a late-time type IIn supernova (SN) via VLT spectroscopy and isolated its explosion date to $\sim$1 yr using archival optical imaging. We briefly touch upon here the wealth of optical, X-ray, and radio archival observations available for this enigmatic source. Due to its relative proximity (3.8$\pm$0.6 Mpc), SN 1996cr ranks among the brightest X-ray and radio SNe ever detected and, as such, may offer powerful insights into the structure and composition of type IIn SNe. We also find that SN 1996cr is matched to GRB 4B 960202 at a 2–3σ confidence level, making it perhaps the third GRB to be significantly associated with a type II SN. We speculate on whether SN 1996cr could be an off-axis or "failed" GRB.

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BACKGROUND

SN 1996cr was discovered by *Chandra* as Circinus Galaxy X-2 [1], an ultraluminous X-ray source which exhibited many traits of a young supernova (SN) interacting with dense circumstellar material (CSM). The Circinus Galaxy (Circinus) is a nearby (3.8$\pm$0.6 Mpc), massive spiral galaxy situated close to the Galactic plane ($b = 3\overset{\circ}{.}8$). Due to its location in the sky, SN 1996cr suffers from $N_{\rm H} \sim 3\times10^{21}$ cm^{-2} ($A_{\rm V} \sim 1.5$) due to our own Galaxy as determined by radio and infrared measurements, and $N_{\rm H} \sim (3$–$5)\times10^{21}$ cm^{-2} ($A_{\rm V}$ $\sim$1.5–2.5) internally based on X-ray column density constraints.

CONFIRMATION AND EXPLOSION DATE CONSTRAINTS

A high quality VLT FORS I spectrum of SN 1996cr taken on 2006 Jan 26 (Fig. 1) confirms it as a type IIn SN. The spectrum is dominated by several narrow emission lines (e.g., Hα, [N II], and [S II]; FWHM$\sim$ 700 km s^{-1}), as well as several strong, complex emission lines of [O I], [O II], [O III] comprised of several partially blended broad emission lines (FWHM$\sim$2000–3000 km s^{-1}) which are red- and blue-shifted with respect to rest wavelengths. Such features imply that the rapidly moving SN material is plowing into a clumpy dense CSM and driving slower shocks into them. The strong, distinct Oxygen peaks suggest the ejecta are perhaps located in a few asymmetric, Oxygen-rich shells or rings.

Narrow-band imaging observations of Circinus with the Taurus Fabry-Perot instrument on the Anglo Australian Telescope between 1995 February 21–28 and 1996 March 15–20 constrain SN 1996cr's explosion date to within $\sim$1 yr. From these images, we estimate SN 1996cr to be $M_{\rm V} \approx -10.2$, or at least $M_{\rm Vc} \approx -15$ when corrected for expected extinction. This provides a strong lower limit, given the explosion date and extinction uncertainties, and indicates that SN 1996cr was at least of average peak brightness among type II SNe [2]. While the optical data provide the tightest constraints on the explosion date, the plentiful archival X-ray and radio data offer invaluable constraints on the surrounding environment. We plot together the soft and hard X-ray fluxes, as well as radio flux densities in a variety of bands (Fig. 1). The early X-ray and radio upper limits imply the presence of either strong early absorption or a low-density cavity immediately surrounding the progenitor. When finally detected, the 0.5–2 and 2–10 keV X-ray fluxes are best-fitted as $\propto t^{1.0}$ and $t^{0.7}$, respectively, whereas nearly all SNe are expected to decline as $\propto t^{-1}$–$t^{-0.4}$ [3] (although observationally there is more scatter [4]). This decade-long rise in the X-ray is most unusual and has only been observed for SN 1987A [5] and marginally for SN 1978K [6]; thus SN 1996cr may be an intermediate object between the extremes of SN 1987A and more typical, luminous SNe. SN 1996cr's rise at radio wavelengths exhibits an unusual convex spectral shape which is poorly fit by conventional models [7] and argues against prolonged early absorption. The strong X-ray and radio emission imply that the CSM is quite dense ($> 10^{-4}\ M_{\odot}\ {\rm yr}^{-1}$), while the lack of broad Hα suggests that the Hydrogen shell was likely cast off prior to explosion. This points to a massive, stripped-core progenitor, perhaps similar to the luminous blue variable η *Carinae* [8]. Notably, the most recent X-ray and radio data demonstrate that SN 1996cr is already one of the brightest X-ray and radio SN on the sky and will likely climb even higher. Thus future monitoring observations should place important constraints on the evolution and nature of the progenitor.

SN 1996CR AS A GAMMA-RAY BURST (GRB)?

Within temporal and positional errors we find that SN 1996cr coincides with BATSE/GRB 4B 960202 [9]. The strict prescription of Wang and Wheeler [10] yields a probability of 4.6%, although this probability is dominated by a few very poorly located sources, while our candidate has a smaller than average 1σ positional error of $0\overset{\circ}{.}88$; the probability that one of the 65 possible candidates instead falls within $3\times0\overset{\circ}{.}88$ of SN 1996cr is only 0.3%. While intriguing, this association remains weak due to the wide range in explosion dates. The link is plausible, however, since the potential progenitor of SN 1996cr appears stripped of its outer envelope, a necessary condition postulated for GRB progenitors [11]. At the distance of Circinus, 4B 960202 would have an observed luminosity of 7×10^{45} ergs s^{-1}, making it the least luminous GRB detected to date; typical GRBs have $\sim 10^{51}$ ergs s^{-1} and even the meager GRB 980425 was 8×10^{47} ergs s^{-1} [12]. 4B 960202's apparently weak luminosity could have several causes. For instance, it could have been intrinsically weak; the underlying physical model that produces GRBs is believed to generate a broad range of luminosities. 4B 960202 could simply lie on the weak tail, perhaps even in the regime of "failed" GRBs, whereby the progenitor may not have shed enough of its outer envelope, forcing the jet to expend the bulk of its energy tunneling out. Or we could simply be viewing

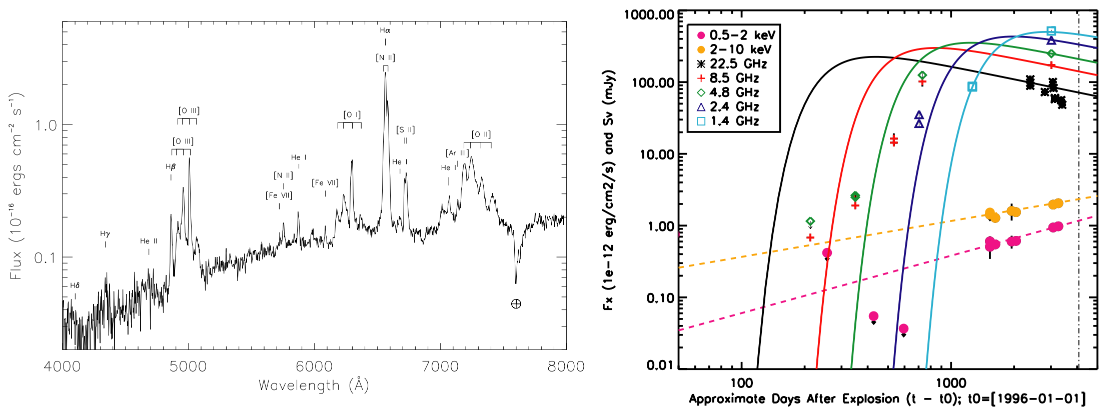

FIGURE 1. *Left:* VLT FORS1 spectrum of SN 1996cr taken on 2006 Jan 26. The spectrum features broad, asymmetric emission complexes, as well as a strong narrow Hα emission line. Such features are typical of late-time SNe interacting with dense circumstellar material (i.e., type IIn). *Right:* Light curves for both the radio (above) and X-ray (below) data. The radio data were fit with a relatively standard ejecta-CSM interaction model, which does well with the late-time radio points, but has difficulty fitting the unusual early-time radio points. Due to the lack of late-time points, the slope of decline is not well determined (aside from the somewhat erratic 22 GHz data, it is not clear whether the radio emission has even "rolled over" yet). Note that even forcing a rather extreme early-time Synchrotron-Self Absorption model on SN 1996cr is not able to acceptably fit the rather odd early data points. The X-ray data from *Chandra* and *XMM-Newton* show a relatively strong and significant rise between 2000-2004 both in the soft and hard bands; this is very atypical for X-ray detected SNe. The strong *ROSAT* soft-band constraints and unusual early-time radio data hint that the progenitor of SN 1996cr may have blown out a relatively low-density cavity immediately prior to its demise.

the GRB off-axis and only be seeing a very small percentage of the overall beamed energy. We note that there are two other type II SNe found to be marginally coincident with GRBs [13]: SN 1999E (GRB 980910, $z = 0.0258$) and SN 1997cy (GRB 970514, $z = 0.059$). While the progenitors of these two SN were likely massive stars, both SNe show broad Hα indicative of a relatively intact progenitor which is at odds theoretically with GRB formation mechanisms [11]. Both GRBs are also significantly underluminous. Taken together, these objects may signal that the physical engines which inevitably drive GRBs may be relatively common in core-collapse SNe.

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